Massachusetts Institute of Technology
Department of Aeronautics and Astronautics
Cambridge, MA 02139

Final Report

On

ROBUST AND ADAPTIVE CONTROL

AFOSR/Eglin AFB Contract FO8635-87-K-0031
MIT OSP NO. 98690

Prepared By:

PROF. LENA VALAVANI

April 1990

Submitted to:

Mr. James Cloutier
Air Force Armament Laboratory (AFSC)
Eglin Air Force Base

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	April 1990	Final Report/Jan 87-Dec89

4. TITLE AND SUBTITLE
Robust and Adaptive Control

5. FUNDING NUMBERS
C: F08635-87-K-0031
PR: 2304
PE: 61102F

6. AUTHOR(S)
Prof Lena Valavani
AFATL Program Manager: Michael Vanden-Heuvel (AFATL/FXG)

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Massachusetts Institute of Technology
Department of Aeronautics and Astronautics
Cambridge, MA 02139

8. PERFORMING ORGANIZATION REPORT NUMBER
MIT OSP No. 98690

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
AFOSR/AFATL
Eglin AFB, FL 32542-5434

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
AFATL-TP-90-14

11. SUPPLEMENTARY NOTES
This TP was not edited in the Technical Reports Section.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

The research, funded by AFOSR/Eglin AFB Contract F08635-87-K-0031, deals with fundamental issues in robust and adaptive control, with emphasis on performance and stability robustness under parametric uncertainty and on the potential applications of such advanced control system design methodologies to the control of high performance vehicles such as the supermaneuverable aircraft and Bank-to-Turn missiles.

Keywords:

14. SUBJECT TERMS
Robust Adaptive Control; Identification in the Time and Frequency Domains; Parametric Uncertainty Analysis

15. NUMBER OF PAGES
11

16. PRICE CODE
(EDC)

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	SAR

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102

PREFACE

This program was conducted by Professor Lena Valavani, Massachusetts Institute of Technology, Cambridge, Massachusetts under contract F08635-87-K-0031 with the Air Force Armament Laboratory, Eglin Air Force Base, Florida 32542-5434. Michael Vanden-Heuvel, AFATL/FXG, managed the program for the Armament Laboratory. The program was conducted during the period from January 1987 to December 1989.

SUMMARY

In this final report we summarize our research activities for the time period 10 November 1986 to 10 November 1989. The research, funded by AFOSR/Eglin AFB Contract FO8635-87-K-0031, deals with fundamental issues in robust and adaptive control, with emphasis on performance and stability robustness under parametric uncertainty and on the potential applications of such advanced control system design methodologies to the control of high performance vehicles such as the supermaneuverable aircraft and Bank-to-Turn missiles.

The research conducted was highly successful and had significant impact upon the theory of robust and adaptive control. The research of La Maire et al deals with a novel formulation of Hybrid Robust Identification algorithms which identify, in real-time, time-domain models of the unknown plant as well as associated modeling error bounds expressed in the frequency domain. This work clarified the tradeoffs involved for robust identification with frequency domain guarantees and established the new philosophy to the robust adaptive control problem: combining robust identification with a robust control structure. The research of Milich et al develops theory and methodologies for designing robust compensators, with guaranteed performance in the presence of large structured and unstructured plant uncertainties. It also has provided a comparison point regarding the attainable performance by the "best robust nonadaptive compensator" versus a truly adaptive controller. The work of Obradovic has addressed the problems of performance robustness under actuator/sensor failures/degradation. The research addressed the problem in its generality as that of robust model matching under parametric uncertainty and provided analysis and design methods for such a formulation. The conservativeness of such methods was pointed out. In particular, when parametric uncertainty is treated as real (rather than complex), the majority of existing methods (including those in the thesis) are as conservative as designs resulting from the small gain theorem. Finally, our research on the design of robust multivariable control systems for Bank-to-Turn Missiles and the Supermaneuverable/HARV aircraft, which has high control redundancy, have brought into focus the advantages of present design methodologies and helped pinpoint directions for future theoretical research.

The funds provided by AFOSR/Eglin AFB provided whole or partial support for one faculty, three Ph.D. and three M.S. graduate students during the contract time period. In addition, two Ph.D. and one M.S. students supported during the contract time period are presently continuing their research to completion.

1. Robust and Adaptive Control

1.1 The Robust Performance Problem/Robust Adaptive Control

Work on the research supported by this AFOSR contract started shortly following the completion of the Ph.D. thesis of D.M. Orlicki, under the supervision of Professors Valavani and Athans. This research pointed to the definite need of on-line spectral monitoring of plant input and output signals, so as to more accurately determine the size of the variable width dead-zone for intermittent adaptation. The motivation was to overcome the conservativeness of suggested solutions while ensuring enhanced system performance via robust adaptive control algorithms. Our research has led to renewed interest in systems identification with emphasis on frequency domain error guarantees on the identified models. This has formed the first component in a robust Identification and Robust Control approach to the high performance design problem under parametric uncertainty, which has evolved as a dominant philosophy in the late eighties and has identified basic issues in the study and control of time varying systems, in this context, relating to performance and stability robustness under parametric and unstructured uncertainty.

In parallel, we have addressed the issue of best achievable performance, with stability robustness under the same assumptions, via fixed parameter compensation. We have identified the inherent limitations and conservativeness of existing methods, thus outlining two major research directions. The first direction, motivated from a robust identification and robust control setting is along the lines of compensation of time-varying systems and quantification of their ensuing performance and robustness properties. The second direction is in seeking alternative structures/choices in the parameterization of optimality based design methods (i.e. H_∞), via judicial choice of free parameters (Q-parameter) so as to ensure performance robustness under parametric uncertainty. The problem of performance robustness under parametric uncertainty is vigorously pursued at present by many distinguished researchers either along the lines of on-line learning schemes (adaptive), as they been newly redefined, or within the framework of robust control structures. Nobody as yet has arrived at a definitive answer to the problem.

1.2 Robust Adaptive Identification in the Time and Frequency Domains

Classical adaptive control algorithms use a postulated dynamic system order, i.e. a transfer function with fixed numbers of poles and zeros, and then use (explicit or implicit) identification to improve the prior estimate of the model uncertain parameters. In robust adaptive control this is necessary, but by no means sufficient. What is required is the development of a new class of adaptive identification algorithms which, with a finite amount of data, produce not only a better nominal model but, in addition, generate a bound in the frequency domain that captures the presence of possible high-frequency model errors. Such bounding of model errors in the frequency domain is required by all nonadaptive design methods so as to ensure stability-robustness by limiting the bandwidth of the closed-loop system. Such identification algorithms did not exist in the classical identification literature; such questions were not even posed. Thus, we believed that it was essential to develop such algorithms and then to incorporate them in the adaptive control problem. A major milestone along these lines has been completed with the publication of Richard LaMaire's doctoral thesis, under the supervision of Professors Valavani and Athans; see publications [2],[3],[14].

We view the robust adaptive control problem as a combination of a robust identifier (estimator) and a robust control-law redesign algorithm. Current robust control design methodologies, such as the LQG/LTR methodology, require: 1) a nominal model, and 2) a frequency-domain bounding function on the modelling error associated with the nominal

model. A new robust estimation technique, which we call a 'guaranteed' estimator, has been developed to provide these two pieces of information for a plant with unstructured uncertainty and an additive output disturbance. This guaranteed estimator uses parametric time-domain estimation techniques to identify a nominal model, and non-parametric frequency-domain estimation techniques to identify a frequency-domain bounding function on the modelling error. This bounding function is generated using discrete Fourier transforms (DFT's) of finite-length input/output data.

Several assumptions are required by the guaranteed estimator. In addition to a priori assumptions on the structure of the nominal model along with coarse, worst-case values of the parameters, we assume that the unmeasurable disturbance is bounded and that a magnitude bounding function on the Fourier transform of the disturbance is known. Further, we assume prior knowledge of a bounding function on the unstructured uncertainty of the plant relative to our choice of nominal model structure. These assumptions allow our time-domain estimator to be made robust to the effects of unstructured uncertainty and bounded disturbances. That is, our time-domain estimator updates the parameters of our nominal model only when there is good (uncorrupted) information. Similarly, the frequency-domain estimator, which has been developed, only updates the model and current bounding function on the modelling error when there is good information. In summary, the guaranteed estimator provides a nominal model plus a guaranteed bounding function, in the frequency-domain, as to how good the model is. Accuracy guarantees in the identifier part of the adaptive controller can be used by the control-law redesign part of the adaptive controller to ensure closed-loop stability, assuming the control-law is updated sufficiently slowly.

All the equations necessary to simulate the performance of these identification algorithms were coded and debugged. Because of the extensive real-time spectral calculations, we decided to use the CYBER supercomputer at Princeton which is available for use by the MIT community at no cost for CPU time. Numerical examples which are simple enough to demonstrate the ideas yet rich enough to capture the potential pitfalls have been designed and simulated.

The simulation results indicate that for the systems tested the time-domain identification algorithms did not work very well. On the other hand, the frequency-domain algorithms worked much better.

In closed-loop identification simulations the richness of the command signal was often not sufficient to excite the plant dynamics so that the identification algorithms could work properly. For this reason, we developed an "intelligent" scheme which would monitor the progress of the identification algorithm and inject probing signals at the appropriate frequencies at the plant input so as to enhance identification. Of course, this would deteriorate (temporarily) performance since a disturbance was injected intentionally in the feedback loop. Better identification, accompanied by higher loop-gains and bandwidths, would improve overall command-following and disturbance-rejection performance after the probing signals were terminated.

The algorithms require extensive real time computations. For sluggish plants the computational requirements are not severe. However, in order to identify and control plants with lightly damped poles the Cyber 205 supercomputer was too slow, for real time control, by a factor of two so as to achieve a closed-loop bandwidth of 5 rad/sec.

These findings cast a tone of pessimism, with respect to CPU requirements, in using real-time identification and high-performance adaptive control for typical aerospace plants that are characterized by lightly damped dynamics and dominant high-frequency

modeling errors. On the other hand, parallel computer architectures can be exploited in this class of algorithms. Thus, more research along these lines is required.

1.3 Best Nonadaptive Compensator Design for Performance-Robustness.

Our research to date has pinpointed the need for a good initial guess for an adaptive compensator, whose parameters are then updated by the adaptive algorithm. We have developed techniques that design the best (from the view point of good command-following and disturbance-rejection) nonadaptive compensator for the given prior plant uncertainty information.

In his doctoral research Mr. David Milich, under the supervision of Professors Valavani and Athans has developed a design technique which will yield the "best" fixed-parameter nonadaptive compensator for a plant characterized by significant unstructured uncertainty; see publications [4] and [7]. The "best" compensator is defined as the one that meets the posed performance (i.e.command-following, disturbance-rejection, insensitivity to sensor noise) specifications and stability-robustness over the entire range of possible plants.

Such a robust design technique can prove useful in a number of ways. First, it yields a systematic procedure for designing feedback systems for uncertain plants with both stability and performance guarantees, not only for the nominal plant but for the entire set of uncertain plants considered. Thus, the feedback loop will be guaranteed to be stable and, in addition, will meet minimum performance specifications for all possible plant perturbations. Second, the solution of this robust design problem will also enable us to quantitatively address one of the most fundamental questions in adaptive control: *what are the performance benefits of adaptive control?* While much attention has been paid to the development of many specific adaptive algorithms, very little consideration has been given to this issue which is, we believe, at the heart of the adaptive control problem. Practical adaptive systems rely upon external persistently exciting signals (to ensure good identification), slow sampling (which helps stability-robustness to unmodeled high frequency dynamics) in addition to extensive real-time computation (to provide safety nets and turn-off the adaptive algorithm when it exhibits instability). All these "fixes" degrade command-following and disturbance-rejection performance and tend to neutralize the hoped-for benefits of an adaptive compensator. In light of these circumstances it is imperative that the decision to use adaptive control, for a real engineering application, must be based upon a quantitative assessment of costs and benefits.

Some of the key issues, and severe difficulties, in the design process have been identified. Conditions for stability-robustness and performance-robustness in the presence of significant unstructured uncertainty have been developed. An a-priori magnitude bound, as a function of frequency, on the unstructured uncertainty is assumed known. In order to reduce the conservatism of the stability and performance considerations with respect to the structured uncertainty, directional information (in the complex plane) associated with the plant-parameter variations is exploited. Unfortunately, this directional information turns out to be closely associated with the so-called *Real-μ problem*, i.e. the problem of calculating structured singular values for real -- rather than complex-valued -- plant modeling errors; this problem has been studied by Doyle and is generically very difficult. Its solution appears to be beyond the state of the art. at least in the near future.

The only reasonable alternative appears to be to translate the prior knowledge of structured uncertainty into an equivalent unstructured uncertainty. It is still a very hard problem to design a compensator with guaranteed performance characteristics in the

presence of these modeling errors. We have transformed the problem into what Doyle calls the *μ-synthesis problem* , which unfortunately is also very hard to solve.

A promising theoretical and algorithmic approach to the solution of the *μ-synthesis problem* has been developed. The theory utilizes the use of Hankel norms in approximating $L\infty$ functions using $H\infty$ functions. Certain procedures have been developed which would indicate whether or not the posed performance specifications are "too tight" for the level of modeling error present. In this case, the control system designer will have to relax the performance specifications, typically expressed as bounds on the sensitivity function maximum singular value, over some frequency ranges.

Maintaining stability in the presence of uncertainty has long been recognized as a crucial requirement for the closed-loop system. Classical designers developed the concepts of phase and gain margin to describe stability-robustness. In the modern control era, conditions for maintaining closed-loop stability in the presence of a single, unstructured (i.e. norm bounded) modeling uncertainty have been formulated in terms of a singular value inequality on the closed-loop transfer function. It is only recently that the issue of multiple modeling uncertainties appearing at different locations in the feedback loop and the related requirement of performance-robustness have been addressed. Multiple unstructured uncertainty blocks, parameter uncertainty, and performance specifications give rise to so-called structured uncertainty. A new analysis framework based on the structured singular value has been developed by J. Doyle to assess the stability and performance robustness of a linear, time-invariant (LTI) feedback system in the presence of structured uncertainty. The structured singular value μ yields a necessary and sufficient condition for robust stability and performance.

While the analysis aspect of LTI feedback design is well-established, the m-synthesis problem remains open. The purpose of this research has been to develop a practical methodology (based on μ-) for the synthesis of robust feedback systems. That is, the design process will ensure the resulting feedback system is stable and performs satisfactorily in the event the actual physical plant differs from the design model (as it surely will). The motivation for an alternative to the D,K iteration is due to the nonconvex nature of the *μ--synthesis problem*. Nonconvexity may lead to local minima, therefore it is essential that several independent methods be available to examine the problem.

This research has produced a new approach to the design of LTI feedback systems. For a given plant, the Youla parameterization describes all stabilizing compensators in terms of a stable, causal operator Q. LTI feedback design may be viewed as simply a procedure for choosing the appropriate Q to meet certain performance specifications. Thus, the design process imposes two constraints on the free parameter Q: (1) stability and causality (i.e. Q must be an $H\infty$ function); (2) Q must produce a closed-loop system that satisfies some performance specification. The design objective of interest here is performance robustness, which can be stated in terms of a frequency domain inequality using the structured singular value.

The CRM initially lifts the restriction of compensator causality and the synthesis problem with uncertainty is examined at each frequency. A feasible set of Q's in the space of complex matrices satisfying the performance specification is constructed. Causality is then recovered via an optimization problem which minimizes the Hankel norm (i.e. the measure of noncausality) of Q over the feasible set. If the problem is well posed (i.e. the performance specifications are not too stringent given the amount of modeling uncertainty),

the resulting compensator nominally stabilizes the feedback system and guarantees robust stability and performance.

The theoretical foundation for the methodology have been established. Next, a research algorithm was written so that we can obtain numerical results. It was applied to two design examples to demonstrate its effectiveness. Excellent robust performance was obtained. However, the current generation of our CRM algorithms require very extensive *off-line* computational resources, because of the several optimization problems that must be solved to design the robust compensator.

1.4 Design of Robust Control for Post-Failure Operation

The basic problem statement here is motivated by the need to reconfigure after actuator failures, whether completely or partially known.

Typically, under no failure/parametric uncertainty, a nominal system design is available for a plant for which a compensator is designed so as to satisfy performance and robustness specifications, under exact knowledge of the system parameters. When a change in the system occurs, as for example, due to a control effector degradation, it is designed to modify the original compensator design to a new one, so that the "failed" system performance remains as close as possible to the original (desired) one. Alternatively, if a failure or failures are anticipated to within certain bounds for given system components, such a robust compensator design can be carried out at the outset, so as to provide the required performance for the system, both at its nominal operating condition as well as in the eventuality of an actual failure within the specified design bounds.

In its most general and abstract setting, then, the problem as formulated in D. Obradovic's doctoral work is that of model matching under parametric and unstructured uncertainty, where the difference between error signals of two systems is minimized in a specified sense. Performance of the "postfailure" system is defined as the value of the "H_∞" norm of a weighted sensitivity transfer function difference between the "nominal"/original and "postfailure" systems.

A nominal compensator designed in the absence of any failures is required in the course of the problem solution. The lower bound for the achievable value of the performance index is associated with the nominal model of the postfailure plant with no modeling uncertainty present resulting from the failure. Necessary and sufficient conditions for "perfect" recovery of the nominal "prefailure" system are derived. Situations where the postfailure plant is square and nonsquare are treated separately. Special attention is paid to the case where the failure is located only in part of the original plant.

The parametric uncertainty resulting from the "failure" is treated both as complex (frequency dependent) as well as real. On the synthesis side, under the assumption of frequency dependent uncertainty, an algorithm is proposed for controller design that maximizes the anticipated uncertainty bound that can be tolerated, for a fixed value of the performance index. The algorithm is based on the "D-K" iteration of Doyle, whose steps are substantially modified. It results in a substantially lower order compensator design with a lesser degree of conservativeness, although it also shares the basic limitation, i.e. local results, of the D-K method.

When the parameter uncertainty is treated as real, a complete analysis methodology in the state space of the "postfailure" system is presented. With the assumption that the

uncertainty enters the elements of the state space linearly and is of bounded magnitude, variously derived Lyapunoy like systems of equations describing the system under consideration are studied and different algorithms for finding the largest hyperbox in parameter space, where specifications of stability and performance robustness are satisfied, are presented. Perhaps the most important result obtained here is the proof of the fact that, for Peterson-Hollot type bounding functions on the parametric uncertainty, the resultant criteria for stability/performance, based on a single-Riccati equation, are as conservative as the "Small Gain Theorem" for the same problem under the same assumptions.

Finally, for special cases when the real parameter uncertainty can be reflected at the plant input, i.e. gain changes, a "gain rescheduling" algorithm of the original compensator design is proposed which minimizes the loss in performance (and the conservativeness of other proposed designs).

1.5 Sensitivity of H_2/H_∞ Designs to Parametric Uncertainty Analysis and Design.

Optimization based control designs (H_2/H_∞) can be extremely sensitive to even very small parametric variation from nominal with potentially serious performance degradation and ultimately instability. This is due to the fact that such designs tend to "invert" the plant over a frequency range of interest. Under parametric deviation from design nominal-as happens in an actual implementation-such implicit pole/zero cancelations are inexact and the design is severely compromised. For example, such a scenario arises in the case of a plant with a pair of lightly damped poles, with imprecisely known damping.

In his M.S. thesis Craig analyzed the effects on the nominal plant of such parametric variation, with an a priori assumed structure and bounds. The analysis has shown, that plants which are "most sensitive", exhibit such sensitivity in the form of a pronounced variation to assumed parametric uncertainty - to within first order - in their open-loop singular values. Designing an "inner-loop" to minimize such variation - i.e. increasing the damping of a "shifted" pair of lightly damped poles - and them carrying out an H_2/H_∞ design was shown by example and simulation to considerably increase tolerance to parametric uncertainty while maintaining specified performance. The designs in [9] constitute a definite improvement over both classical compensation and H_2/H_∞ controllers without the inner loop, but with judicious choice of weights. We are continuing our research to formalize and systematize such results within a choice framework for the parameter [17].

Furthermore, our research continues into alternative choices for the Q-parameter - via a constrained optimization problem - so as to "suboptimize" simultaneously for the H2 norm of an H_∞ design for a specified performance level . This is represented in the doctoral research of B. Ridgely, currently in progress[15].

1.6 Time-Varying Systems

We are also continuing our work on performance robustness and stability issues arising in the context of compensation in a time-varying process as arises form intermittent identification and control parameter adjustment. Preliminary results were obtained while the contract was still in effect and were completed subsequently [13]. This work is represented in P.Voulgaris' Ph.D. research which is currently ongoing under the supervision of Professors Dahleh and Valavani.

2. State of the Art Designs for Bank -to Turn Missiles and the Supermaneuverable Aircraft.

We have applied the available modern designs H_2/H_∞ to the multivariable control of a Bank-to Turn Missile Model and the Supermaneuverable/HARV aircraft so as to make a judgement as to whether high performance robust designs offer an advantage for such systems and also in order to make a comparison between the available methodologies for fixed parameter designs ($H2/H_\infty$).

Significant benefits were realized by using the LQG/LTR (H_2) method in the BTT missile, with subsequent suggestions for modification of existing vehicle architectures - as well as scheduling parameters - for improved performance. This work was carried out by an Army officer studying at MIT, and is represented in [1],[6].

For the supermaneuverable/HARV both H_2 and H_∞ methods were used for design. This was one of the very first realistic examples where the H_∞ method was applied. A comparison showed that the two methods are equivalent with H_∞ holding a slight advantage over H_2 (LQG/LTR). Given the control redundancy built into this aircraft, it was possible to design control systems that maintained good performance (virtually unaltered) in the presence of two failures and satisfactory performance in the presence of three failures. Such results are contained in [5], [12].

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
DEPARTMENT OF AERONAUTICS AND ASTRONAUTICS

RESEARCH ON ROBUST AND ADAPTIVE CONTROL
AFOSR/Eglin AFB Contract FO8635-97-K-0031

List of Publications
November 10, 1986 to November 10, 1989

[1] C.L. Shepherd, "Antopilot Designs for Bank-to-Turn Flight Vehicles," M.S. Thesis, MIT, January 1987.

[2] R.O. La Maire, "Robust Time and Frequency Domain Estimation Methods in Adaptive Control", Ph.D. Thesis, M.I.T., May 1987.

[3] R.O. La Maire, L. Valavani, M.Athans and G. Stein, "A Frequency Domain Estimator for Use in Adaptive Control Systems," Proc. American Control Conference, Minneapolis, MN, June 1987.

[4] D. Milich, "A Methodology for the Synthesis of Robust Feedback Systems," Ph.D. Thesis, MIT, February 1988.

[5] P. Voulgaris, "High Performance Multivariable Control of the "Supermaneuverable F-18/HARV Fighter Aircraft," M.S. Thesis, MIT, May 1988.

[6] C. Shepherd and L. Valavani," Autopilot Design for Bank-to-Turn Missiles," Proc. American Control Conference, Atlanta, GA June 1988.

[7] D. Milich, M.Athans, L. Valavani, and G. Stein, "A Method for Designing Robust Multivariable Feedback Systems," Proc. Conference on Decision and Control, Austin, TX, December 1988.

[8] P. Voulgaris and L. Valavani, "High Performance Multivariable Control for the Supermaneuverable/HARV Aircraft," AIAA Conference, Boston, MA August 1989.

[9] I. Craig, "Parametric Sensitivity Studies of Modern Control Synthesis Methods," M.S. Thesis, MIT, May 1989.

[10] D. Obradovic and L.Valavani, "Robust Stability and Performance in the Presence of Real Parameter Perturbation - A Unified Analysis Approach," Proc. of the IEEE Conference on Decision and Control, Tampa FL, December 1989.

[11] D. Obradovic, "Design of a Robust Control System for Postfailure Operation," Ph.D. Thesis, MIT, May 1990.

[12] P. Voulgaris and L. Valavani, "High Performance H2 and H∞ Designs for the "Supermaneuverable" F18/HARV Fighter Aircraft," AIAA Journal on Guidance, Control and Dynamics, July - August 1990 (to appear).

[13] M. Dahleh, P. Voulgaris, L. Valavani, "Optimal Rejection of Bounded Persistent Disturbances in Periodic Systems," Proc. IEEE Conference on Decision and Control, Hawaii, Dec. 1990.

[14] R. La Maire, L. Valavani, M. Athans and G. Stein, "Robust Time and Frequency Domain Estimation Methods in Adaptive Control," Automatica, January 1991 (to appear).

[15] B. Ridgely, "H∞ Optimization with an H2 Superoptimization Criterion," Ph.D. Thesis, MIT, in progress.

[16] P. Voulgaris, "Control Analysis and Design for Time-Varying Systems," Ph.D. Thesis, MIT, in progress.

[17] A. Inoue, "Design Methods for Robustly Performing Systems Under Parametric Uncertainty," M.S. Thesis, MIT, in progress.